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Measurement of the electroweak properties of τ leptons in the Belle experiment (Precise measurement of the τ lepton lifetime)

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Abstract

We report a high precision measurement of the τ-lepton lifetime using data collected with the Belle detector at the $\Upsilon(4S)$ resonance and 60 MeV below. We measure the τ lifetime to be $\tau = (290.17 \pm 0.53(\text{stat.}) \pm 0.33(\text{syst.})) \cdot 10^{-15}$ s, which is almost twice more precise than the current world average. We also set the upper limit on the relative lifetime difference between positive and negative τ leptons to be $|\tau_{\tau^+} - \tau_{\tau^-}/\tau_{\text{average}}| < 7.0 \times 10^{-3}$ at 90% CL. This is a first measurement on this quantity.

Keywords: τ-lepton, lifetime, lepton universality, CPT invariance

1. Introduction

Lepton universality in the charged lepton sector of the standard model (SM) is the fundamental assumption about the lepton flavor-independent structure of the charged weak interaction. It is introduced in the theory as an equality of the coupling constants for e^-, μ^- and τ^-: $g_e = g_\mu = g_\tau$. This universality can be experimentally tested by comparing the rate of the leptonic decays: $\tau^- \to e^-\overline{\nu}_e\nu_\tau$, $\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$ and $\mu^- \to e^-\overline{\nu}_e\nu_\mu$. The decay width for these decay with electroweak radiative corrections reads[1],

$$\Gamma(L^- \to \ell^-\overline{\nu}_\ell\nu_L) = \frac{\mathcal{B}(L^- \to \ell^-\overline{\nu}_\ell\nu_\tau)}{\tau_L} = \frac{g_L^2 g_\ell^2}{32M_W^4}\frac{m_L^5}{192\pi^3} f(m_\ell^2/m_L^2) r_{\text{EW}}^L, \quad (1)$$

$$f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \log x, \quad (2)$$

$$r_{\text{EW}}^L = \left(1 + \frac{3}{5}\frac{m_L^2}{M_W^2}\right)\left(1 + \frac{\alpha(m_L)}{2\pi}\left(\frac{25}{4} - \pi^2\right)\right), \quad (3)$$

where $L^-(L^- = \mu, \tau)$ is the initial lepton, $\ell(\ell = \mu, e)$ is the final lepton, $m_L(m_\ell)$ and $g_L(g_\ell)$ are the mass and the coupling constant of initial (final) lepton, respectively. τ_L is the lifetime of the initial lepton. M_W and $\alpha(m_L)$ are W^- boson mass and the fine-structure constant at the energy scale of m_L, respectively. For $L = \tau$, the value of the EW radiative correction r_{EW} is 0.9960. The ratios of the coupling constants, g_τ/g_μ and g_τ/g_e, can be extracted as

$$\frac{g_\tau}{g_\mu} = \sqrt{\mathcal{B}(\tau^- \to e^-\overline{\nu}_e\nu_\tau)\frac{\tau_\mu}{\tau_\tau}\frac{m_\mu^5}{m_\tau^5}\frac{f(m_e/m_\mu)}{f(m_e/m_\tau)}\frac{r_{\text{EW}}^\mu}{r_{\text{EW}}^\tau}} \quad (4)$$

$$\frac{g_\tau}{g_e} = \sqrt{\mathcal{B}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)\frac{\tau_\mu}{\tau_\tau}\frac{m_\mu^5}{m_\tau^5}\frac{f(m_e/m_\mu)}{f(m_\mu/m_\tau)}\frac{r_{\text{EW}}^\mu}{r_{\text{EW}}^\tau}}. \quad (5)$$

For an accurate test of lepton universality, precise measurements of the branching fractions, $\mathcal{B}(\tau^- \to e^-\overline{\nu}_e\nu_\tau)$ and $\mathcal{B}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)$, the τ mass and τ lifetime (τ_τ) are necessary. We reported our measurement of the τ mass in Ref. [2]. In this talk, we report a result of the measurement of the τ lifetime using Belle data (Details are described in Ref. [3]).

According to the last report from Heavy Flavor Averaging Group (HFAG)[4], the lepton universality was confirmed in the g_τ/g_μ and g_τ/g_e ratios with the accuracy of 0.2 %:

$$g_\tau/g_e = 1.0024 \pm 0.0021, \quad g_\tau/g_\mu = 1.0006 \pm 0.0021.$$

While the ratio of the branching fraction of W^- boson

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decay to $\tau\bar{\nu}_\tau$ and the average of $\mu\bar{\nu}_\mu$ and $e^-\bar{\nu}_e$ was found to be 2.6 standard deviations differ from unity.

$$\frac{2\mathcal{B}(W^- \to \tau^-\bar{\nu}_\tau)}{\mathcal{B}(W^- \to \mu^-\bar{\nu}_\mu) + \mathcal{B}(W^- \to e^-\bar{\nu}_e)} = 1.066 \pm 0.025.$$

So the further improvement of the accuracy of the test of lepton university with leptonic decays of τ is an important task yet. In particular, the reduction of the uncertainty of the τ lifetime is essential. If one can reduce it to the negligible level, the lepton university could be tested with the accuracy of about 0.1% even with the current values of the τ mass and the branching fraction uncertainties.

2. Method of τ lifetime measurement at Belle

This analysis (Ref. [3]) is based on the data with the integrated luminosity of 711fb^{-1} collected with the Belle detector [5, 6] at the KEKB asymmetric-energy (3.5 GeV and 8 GeV) e^+e^- collider [7] operated at the $\Upsilon(4S)$ resonance and 60 MeV below. The data sample corresponds to 653×10^6 $\tau^+\tau^-$ pair production including data with two inner detector configurations. A 2.0 cm radius beam pipe and a 3-layer silicon vertex detector (SVD1) are used for the first sample of 157 fb^{-1}, while a 1.5 cm radius beam pipe, a 4-layer silicon detector (SVD2) and a small-cell inner drift chamber are use to record the remaining 554 fb^{-1}. For lifetime measurement we analyze events where both τ's decay to three charged pions and a neutrino,

$$e^+e^- \to \tau^+\tau^- \to \pi^+\pi^-\pi^+\nu_\tau + \pi^-\pi^+\pi^-\bar{\nu}_\tau, \qquad (6)$$

(or shortly $(3\pi)^+ - (3\pi)^-$).

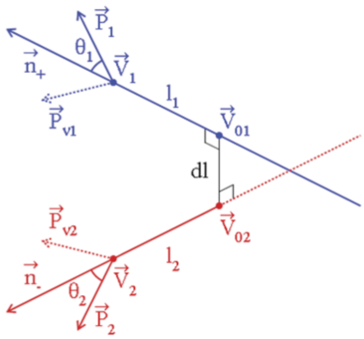

Figure 1: Schematic view of the $\tau^+\tau^-$ pair production in the laboratory frame.

Asymmetric-energy collider, such as KEKB, has a special merit for the measurement of the τ lifetime. At

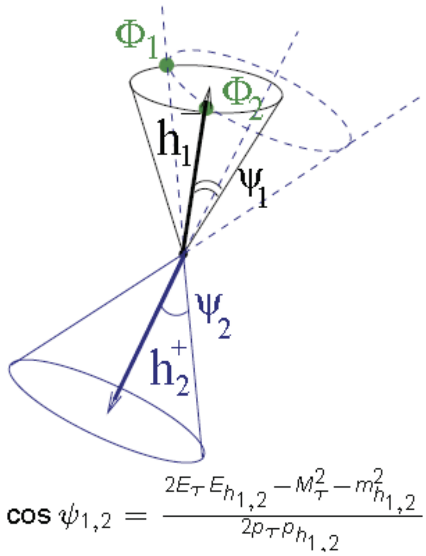

Figure 2: Schematic view of $\tau^+\tau^-$ production in the e^+e^- center-of-mass system. $\Psi_{1,2}$ denote the angle between the τ flight direction and the hadron system for $h_1 = (3\pi)^-$ and $h_2 = (3\pi)^+$, respectively.

an asymmetric-energy collider, the angle between τ^+ and τ^- in the laboratory frame is smaller than 180°, so their production point, i.e, the beam collision point, can be determined as the intersection of two trajectories defined by the τ-lepton decay vertices and their momentum directions in the laboratory system (see Fig.1). Although the momentum direction for each τ lepton can not be measured directory due to missing a neutrino, one can reconstruct it in the laboratory frame as follows. In the center-of-mass system (CMS), the angle ψ^* between the momentum of the hadronic system and that of the τ-lepton is given by

$$\cos\psi^* = \frac{2E_\tau^* E_X^* - m_\tau^2 - m_X^2}{2P_X^* \sqrt{(E_X^*)^2 - m_\tau^2}},$$

where E_X^* (P_X^*) represents the energy(momentum) of the hadronic system $X = (3\pi)$ in CMS, and m_X is the mass of the system X. Using this relation and the fact that the τ^+ and τ^- leptons are emerged back to back with the energy E_τ^* equal to the beam energy in the CM frame, one can determine the direction of the τ-lepton with twofold ambiguity as shown in Fig. 2. (In this analysis, we use the average axis among two-solutions, since the analysis of MC simulation shows there is no bias due to this choice.) The four-momenta of each τ-lepton in the laboratory system can then be determined by boosting τ four-momenta in CMS to the laboratory frame, each passing through the corresponding τ decay vertex $\vec{V}_i$ for the positive ($i = 1$) and negative ($i = 2$) τ leptons, respectively. We approximate the trajectory of τ-leptons in the magnetic field of the Belle detector with a straight line and obtain the $\tau^+ \tau^-$ production point from these lines. Due to the finite detector resolution, these straight lines do not intersect at one point; the three-dimensional separation between these lines is characterized by the distance $d\ell$ between two points ($\vec{V}_{01}$ and V_{02}) of closest approach. The typical size of $d\ell$ is ~ 0.01cm. The flight length (ℓ_i) for τ^+ (τ^-) can be defined as the distance between the points $\vec{V}_1$ and $\vec{V}_{0,1}$ ($\vec{V}_2$ and $\vec{V}_{0,2}$). The τ proper time (multiplied by the speed of light) are then given by

$$(ct)_i = \frac{|V_i - V_{0,i}|}{(\beta\gamma)_i},$$

for the positive and negative τ leptons, independently (Fig. 1). In this way, one can measure the τ lifetime without a priori knowledge of the position of the beam interaction point. This special feature of the asymmetric-energy B-factory experiments allows a high precision measurement of the τ-lepton lifetime.

We apply following criteria to select signal $(3\pi)^+ - (3\pi)^-$ events: there are six charged pions with zero net charge and no other tracks. the thrust value in CMS is greater than 0.9. there are three pions with ± 1 net charge in each hemisphere separated by the plane perpendicular to the thrust axis; there are no additional K_S^0, Λ and π^0 candidates; the absolute value of the transverse momentum of the 6π system is greater than 0.5 GeV/c; the mass of the 6π system ($M(6\pi)$) should be 4 GeV/c^2 < $M(6\pi)$ < 10.25GeV/c^2; the pseudomass of each triplet pions, $M_{\min} = \sqrt{m_{3\pi} - 2(E_{\rm beam} - E_{3\pi})(E_{3\pi} - P_{3\pi})}$, must be less than 1.8 GeV/c^2; each triplet pion vertex-fit quality must be $\chi^2 < 20$. the distance ($d\ell$) of the closest approach of the τ^+ and τ^- trajectories in laboratory frame satisfies $d\ell < 0.03$ cm;

Finally 1,148,360 events are selected with the background contamination of about 2%, where the dominant background comes from the continuum $e^+e^- \to q\overline{q}(q = u, d, s)$ events. The background from $e^+e^- \to c\overline{c}$ is small (0.2%).

The measured τ decay time distribution is parameterized in the form;

$$\mathcal{P}(ct) = \mathcal{N} \int e^{ct'/\lambda_\tau} R(ct - ct'; \vec{P}) d(ct') + \mathcal{N}_{\rm uds} R(ct, \vec{P}) + B_c(ct), \quad (7)$$

where ct is the proper decay time (multiplied the speed of light) measured in the rest frame of the τ lepton, The parameter $\mathcal{N}$ is the normalization constant and λ_τ is the estimator of the τ lifetime $c\tau_\tau$,

$$c\tau_\tau = \lambda_\tau + \Delta_{\rm corr},$$

where $\Delta_{\rm corr.}$ is the correction factor to λ_τ to relate the true τ_τ value. $\mathcal{N}_{uds}$ is the contribution of the background from $e^+e^- \to q\overline{q}(q = u, d, s)$ and $B_c(ct)$ is the contribution of the background from $e^+e^- \to c\overline{c}$. The function $R(x; \vec{P})$ represents the detector resolution. We parameterize it by the form

$$R(x; \vec{P}) = (1 - Ax) \cdot \exp\left(-\frac{(x - P_1)^2}{2\sigma^2}\right),$$
$$\sigma = P_2 + P_3|x - P_4|^{1/2} + P_4|x - P_4| + P_5|x - P_4|^{3/2}, \quad (8)$$

where four parameters, $\vec{P} = (P_2, ..., P_5)$, are used to parametrize σ. The term Ax takes into account the possible shift of the resolution function. The best-fit value for A is obtained to be (2.5 ± 0.2) cm^{-1}. An example of the fitting of the resolution is shown in Fig. 3.

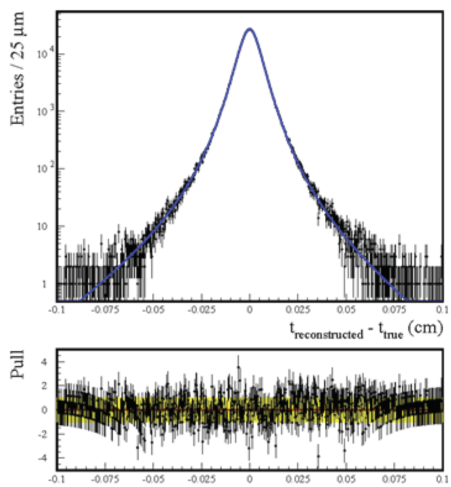

Figure 3: Distribution of the difference between the reconstructed and true τ decay time (ct). The line is the fit to the resolution function parameterized by Eq. (8).

3. Lifetime results

Figure 4 shows the measured proper time distribution and the result of the fit to Eq. (7). In the fit, the parameters λ_τ $\mathcal{N}$ and $\vec{P} = (P_2, ..., P_5)$ are floated, while the asymmetry A is fixed to $A = 2.5$cm^{-1} since it is correlated with λ_τ, The backgrounds from u, d, s and c, b are fixed to the expectation from the MC. The goodness of the fit is $\chi^2/NDF = 143/153$. The obtained value of the lifetime estimator λ_τ is (86.53 ± 0.16) μm. Applying the correction $\Delta_{\rm corr} = 0.46$ μm, the value determined from the relation between the true and reconstruction $c\tau_\tau$ by MC, the obtained value of $c\tau_\tau$ is

$$c\tau_\tau = (86.99 \pm 0.16(\text{stat.}))\ \mu m.$$

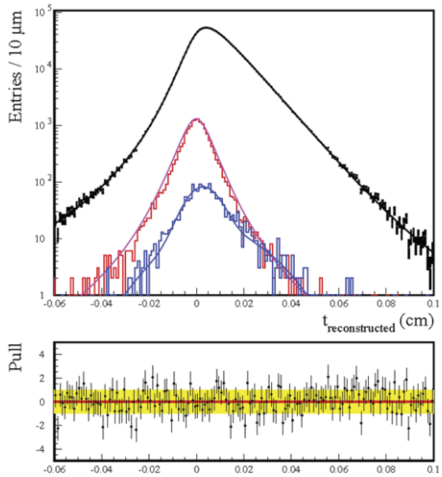

Figure 4: Distribution of the measured decay time ct (closed circle with errors). The solid (black) line is the result of the fit. The red histogram is the MC prediction for the sum of the $e^+e^- \to q\bar{q}$ ($q = u, d, s$) and the two-photon background, While blue histogram is the $e^+e^- \to c\bar{c}$ background. The distribution of residual for the fit is shown in the bottom panel.

We make an extensive study on the systematic uncertainties of the measurements. The main sources are summarized in Table 1.

Table 1: Summary of systematic uncertainties for the life time $c\tau_\tau$ measurement.

Source	$\Delta(c\tau_\tau)$ (μm)
Silicon vertex detector alignment	0.090
Asymmetry fixing	0.030
Fit range	0.020
Beam energy, ISR, FSR	0.024
Background contribution	0.010
τ-lepton mass	0.009
Total	0.101

The largest systematic is from the alignment of the SVD. In this experiment, the final alignment of the SVD is carried out by using cosmic-rays with the local uncertain of 10 μm for the shift and 0.1 m rad for the rotation. Using the special MC samples that takes into account the mis-alignment effects, the systematic uncertainty caused by the misalignment of the tracking detectors is estimated to be 0.090 μm. Since both τ-pair production point and the decay vertex are reconstructed event-by-event basis and only these difference are used for the lifetime measurement, the global shift on the SVD is found to be insensitive to this measurement.

As a additional check of the results, we compare the results by dividing the data into two non-intersecting sample by the azimuthal angle of the momentum direction. We also compare the results from two independent configuration of the SVD detectors (SVD1 and SVD2). These cross checks provide the consistent results within statistical errors.

The systematic uncertainty due to fixing the asymmetric parameter A in Eq,(8) is estimated from the difference between with and the without the asymmetry term $(1 - Ax)$ in the equation. The uncertainty of the initial and final state radiation description by the KKMC generator[8] is check by using $e^+e^- \to \mu^+\mu^-\gamma$ events. The uncertainty of the background from $q\bar{q}$ contribution are estimated by changing these components conservatively from -50% to $+150\%$. Adding all sources of the systematic uncertainties by quadrature, we estimate the total uncertainty to be 0.10 μm.

The obtained results for the product of the speed of light and the lifetime, and the lifetime are

$$c\tau_\tau = (86.99 \pm 0.16(\text{stat}) \pm 0.10(\text{syst})\ \mu m,$$
$$\tau_\tau = (290.17 \pm 0.53(\text{stat}) \pm 0.33(\text{syst})\ \text{fs}.$$

Belle result on τ_τ are compared with previous measurements [9, 10, 11, 12] in Fig. 6. The result is almost twice more precise than the current world average[13]. With the new Belle τ_τ result, the revised ratios of g_τ/g_e and g_τ/g_μ are

$$g_\tau/g_e = 1.0031 \pm 0.0016,\ g_\tau/g_\mu = 1.0013 \pm 0.0016. \quad (9)$$

By including the new Belle result, the uncertainty of the ratios are improved by a factor of 1.3 in comparison with the last HFAG result[4], and now the g_τ/g_e ratio is almost 2 standard deviation away from the unity. The same tendency is also seen in a two dimensional plot of the leptonic branching fraction $\mathcal{B}(\tau^- \to e^-\bar{\nu}_e\nu_\tau)$ versus τ lifetime (see Fig. 6).

4. Lifetime difference between positive and negative τ leptons

The present PDG listing [13] provides only the average lifetime of the positive and negative τ leptons.

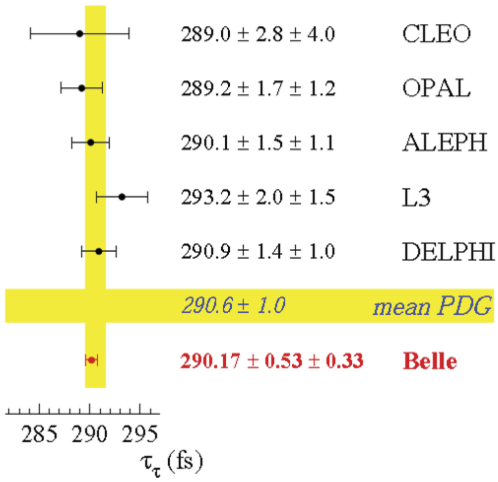

Figure 5: Summary of the τ lifetime measurements. Results from other experiments are taken from Refs [9, 10, 11, 12, 13].

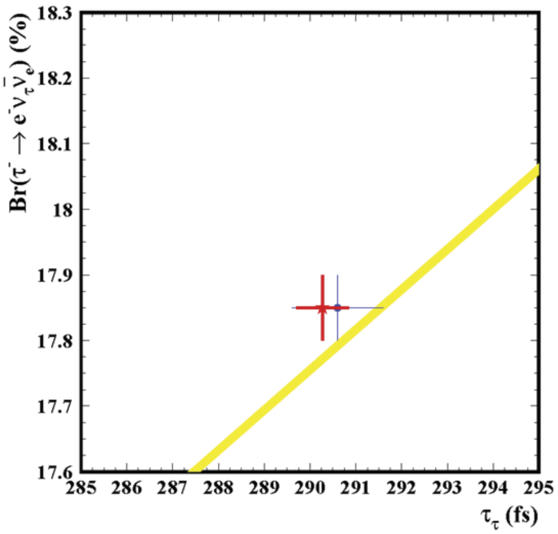

Figure 6: Two dimensional plot of the leptonic branching fraction $\mathcal{B}(\tau^- \to e^-\overline{\nu}_e\nu_\tau)$ versus τ lifetime (τ_τ). The world average before and after including this measurement are shown by red and blue cross bars, respectively. The expectation from the SM is shown by yellow line where the line width is determined by the uncertainty of the τ lepton mass.

Our measurement determines the lifetime for positive and negative τ leptons separately. From the fits to the decay time distributions for positive and negative τ (see Fig. 7), we obtain the upper limit on the relative lifetime difference between τ^+ and τ^- to be

$$|\tau_{\tau^+} - \tau_{\tau^-}/\tau_{\text{average}}| < 7.0 \times 10^{-3}$$

at 90% CL. The upper limit is determined by the statistical error and the systematic uncertainty of the lifetime difference is at least one order of magnitude smaller than the statistical one. This is the first measurement on this quantity.

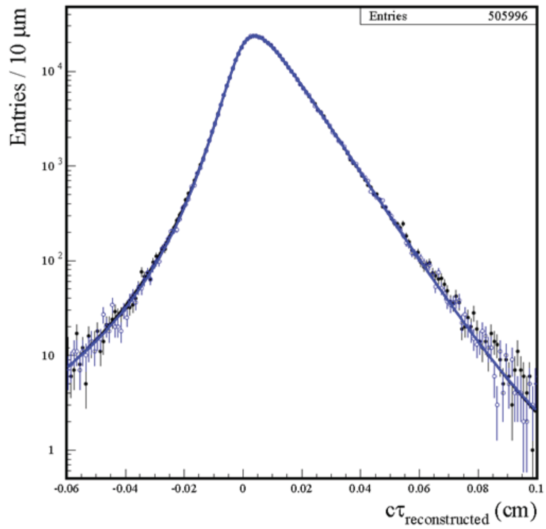

Figure 7: Distribution of the measured decay length ct for τ^+ (closed circles) and τ^- (open circles). The solid lines are the fit results.

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